

UNITED STATES PATENT APPLICATION

of

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for

**MAGNETIC PROCESS FOR REMOVING HEAVY METALS
FROM WATER EMPLOYING MAGNETITES**

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MAGNETIC PROCESS FOR REMOVING HEAVY METALS 2 FROM WATER EMPLOYING MAGNETITES

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BACKGROUND OF THE INVENTION

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1. Government Rights

6 This invention was made with Government support Contract Number W-7405-ENG-
7 36 awarded by the United States Department of Energy to the Regents of the University of
8 California. The Government has certain rights in the invention.

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2. The Field of the Invention

10 The present invention relates to the use of magnetites and magnetic separation to
11 bind and remove heavy metals from water. More specifically, the present invention relates
12 to binding heavy metals in water to magnetite and then removing those bound heavy metals
13 from the water by magnetic separation. In one aspect of the invention the heavy metal-
14 containing magnetite is removed from the water by flowing the water past a solid matrix
15 displaying remnant magnetism.

16

3. The Relevant Technology

17 Water pollution is a serious problem in the United States and throughout the world.
18 In the last several decades water pollution has been the subject of increased government
19 scrutiny and regulation. In response to the need for clean drinking water and the need to
20 maintain clean water in rivers, lakes, oceans, and wet lands, detailed statutory and regulatory
21 schemes have been developed at the state and local levels in the United States. These
22 statutory and regulatory schemes relate to many types of activities that can produce water
23 pollution. Such activities include everything from controlling the quality of run off from
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1 farming operations and in storm drainage systems, to the regulation of industrial, mining,
2 and commercial activities. Almost any activity that produces or has the capability of
3 producing significant quantities of tainted water will be regulated by state and federal
4 regulations. Several regulatory agencies deal extensively with the regulation of water
5 emissions. Some of these agencies include the United States Environmental Protection
6 Agency (EPA) which has broad regulatory authority, the United States Coast Guard which
7 regulates the use of navigable waters, state Oil and Gas Boards which regulate produced
8 waters at well sites, and state and federal agencies dealing with mine regulation.

9 Various water pollutants, and specific activities which have the capability of
10 producing water pollution, are the subject of water quality regulations. Materials that may
11 be regulated range from pesticides and fertilizers, to oil and numerous chemicals and
12 hazardous materials. Any material that may arguably be detrimental if placed in the water
13 supplies of the nation are subject to regulation and controlled emission.

14 Heavy metals are one class of problematic water pollutant which is encountered
15 widely in the environment. Essentially all transition metals can exist as dissolved ions in
16 water. Examples of heavy metals which may become water pollutants include lead,
17 manganese, cobalt, cadmium, and others. These materials present significant water pollution
18 problems when they exist in a stream or water supply. Consuming water containing heavy
19 metals is detrimental to the health of humans and animals alike. Heavy metal poisoning can
20 be a serious public health issue. Accordingly, there is significant interest in removing heavy
21 metals from water supplies.

22 At the same time, removal of heavy metals from water in bulk is a difficult and
23 expensive process. While the chemistry of heavy metals is well understood, applying that
24 chemistry to remove heavy metals from water in the environment and at ambient conditions
25 has proven difficult and expensive. These processes often require large bulky processing

1 facilities and can produce waste products which are themselves hazardous and pose difficult
2 disposal issues.

3 Adding to the problem is that fact that some old industrial and mining operations
4 have produced heavy metal emissions over many decades and in some cases for more than
5 a century. Many of these operations pre-date modern water pollution control regulation and
6 the development of modern water pollution control technology. Thus, these operations
7 produced heavy metal emissions with not much effort directed to removal of the metals from
8 the water or limitation of the pollutants prior to their release into the environment.

9 Where these types of facilities have continued in operation, they have been brought
10 up to standards by the application of the necessary modifications as required by the
11 regulatory schemes mentioned above. However, in cases where mines and other industrial
12 facilities closed down prior to the implementation of pollution control systems and
13 technology and the implementation of modern regulatory schemes, it is quite possible for
14 such facilities to continue to produce water emissions tainted by heavy metals.

15 This is particularly true of mining operations which may have ground water flowing
16 through them and exits into local streams and drinking water. Heavy metal contamination
17 of natural water sources continues to be a problem in the mining communities long after
18 mining has ceased. Due to the undesirability of heavy metal pollution in the water, much
19 effort and expense is necessary to remediate these problems, often with less than adequate
20 results.

21 Many problems exist with traditional heavy metal or water treatment remediation
22 methods. As mentioned above, the chemistry of the metals involved is well known, so the
23 various known processes are documented. One such method is metal hydroxide
24 precipitation to remove heavy metals; however, this and many other conventional methods
25 involve adding large quantities of chemicals to the waste stream which might contain
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1 quantities of contaminants at levels less than parts per thousand. These types of procedures
2 can result in large quantities of metal-contaminated or metal-containing precipitate. As
3 mentioned above, the disposal of the resultant metal-laden precipitate presents disposal
4 problems of its own, particularly if the precipitate has the potential of later leaching of metals
5 back into the environment.

6 Most of the known processes require complex and bulky equipment. These
7 processes are expensive and sometimes result in less than adequate cleaning of the water.
8 Conventional processes often result in a waste material that itself is hazardous and must be
9 disposed of using expensive techniques which are the subject of further EPA regulation.

10 Thus, it would be a significant advancement in the art to provide improved methods
11 and apparatus for cleaning water. More particularly, it would be a significant advancement
12 in the art to provide such methods and apparatus which were capable of removing heavy
13 metals from water. It would be an advancement in the art to provide such methods and
14 apparatus which were capable of removing heavy metals from water without the use of
15 chemical additives that produce large quantities of unstable chemical sludge. It would be a
16 further advancement in the art to provide such methods and apparatus that operated using
17 facilities significantly smaller than conventional water treatment facilities. It would be an
18 advancement in the art to provide such methods and apparatus which were less costly to
19 operate than conventional apparatus, and which were capable of producing waste products
20 that were not themselves hazardous.

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23 **BRIEF SUMMARY OF THE INVENTION**

24 The methods and apparatus of the present invention have been developed in
25 response to the present state of the art, and in particular, in response to the problems and
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1 needs in the art that have not yet been fully solved by currently available water treatment
2 methods and apparatus. To achieve the desired advantages mentioned above, and in
3 accordance with the invention as embodied and broadly described herein in the preferred
4 embodiment, methods and apparatus for removing heavy metals from water are disclosed
5 herein.

6 In one aspect the present invention relates to a process for removing heavy metals
7 from water. As discussed above, the removal of heavy metals from water is a major problem
8 in maintaining and improving water quality. The process involves introducing or forming
9 magnetite in water containing heavy metals such that the heavy metals are bound to the
10 magnetite. Magnetite is an iron oxide with the formula Fe_3O_4 . Magnetite occurs as a mineral
11 and is a multi-valence oxide having both Fe(II) and Fe(III) in the same inverse spinel
12 structure. It is found that magnetite is extraordinarily magnetic. Also, because of the inverse
13 spinel structure of the mineral, it is possible for other metals to become incorporated into the
14 magnetite crystal matrix. Metals can be incorporated chemically, or they can be absorbed
15 onto the existing magnetite structure. In either event, these phenomena will be referred to
16 herein as "binding" or having the metal "bound" to the magnetite. These terms are used to
17 incorporate both chemical binding and adsorption for purposes of describing the present
18 invention. In addition, the resulting products will be referred to collectively as "magnetite."
19 Compounds which include metals chemically bonded within the magnetite structure are
20 sometimes referred to in the art as "ferrites." However, it will be understood, that for the
21 purposes of this invention, such "ferrite" compounds fall within the scope of the term
22 "magnetite" as used herein.

23 The process of the present invention includes the steps of introducing magnetite to
24 a quantity of water containing at least one heavy metal. One example of such water is mine
25 drainage. Some of the experimental examples provided below use mine effluent from the
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1 Leadville mine drainage tunnel at Leadville, Colorado in order to demonstrate the present
2 invention. Next, magnetite is mixed with the water, or formed in-situ, such that at least a
3 portion of, and preferably most of, the heavy metal in the water is bound to the magnetite.
4 Once the heavy metal is bound to the magnetite, the magnetite and heavy metal are removed
5 by the application of a magnetic field. Since the magnetite is magnetic, it is easily separated
6 from water by the application of a magnetic field in the presence of a magnetically active
7 capturing matrix.

8 In most embodiments of the present invention the application of a magnetic field is
9 accomplished by flowing the water through a solid magnetized matrix such that the
10 magnetite magnetically binds to the solid matrix. The magnetized matrix may, for example,
11 comprise steel wool. The steel wool can either be pre-magnetized, and therefore demonstrate
12 "remnant magnetism," or the steel wool can be placed under the influence of an external
13 magnetic field generated by either an electromagnet or a permanent magnet.

14 In this configuration good results are achieved when the superficial velocity of the
15 water through the matrix is in the range of from about 0.5 cm/sec to about 2.0 cm/sec. More
16 preferably, the superficial velocity of water through the matrix is about 1 cm/sec. In order
17 to adjust to larger or smaller inlet flow rates of water, the apparatus of the present invention
18 is modular and scalable such that different flow rates can be handled while maintaining the
19 superficial velocity within the preferred range.

20 Magnetite can be introduced to the process in several ways. The two main types of
21 introduction of magnetite include the introduction of pre-formed magnetite to the water and
22 the formation of magnetite in situ. The introduction of pre-formed magnetite may involve
23 simply adding commercially available magnetite to the water to be treated. When using this
24 process it is expected that the heavy metal removed will be metal adsorbed onto the
25 magnetite.

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1 Alternatively, the magnetite may be made in situ. In this process, effective
2 quantities of Fe(II) and Fe(III), such as in the form of Fe(II) sulfate and Fe(III) sulfate, are
3 added to the water. It is believed that magnetite is formed in a two stage process. First
4 "green rust," which is (Fe(II) oxy-hydroxides), are formed. This is followed by dehydration
5 with and incorporation of Fe(III) to form magnetite. It is believed that in-situ formation of
6 magnetite (ferrite) involves the incorporation of at least a portion of the heavy metal into the
7 magnetite structure. Thus, the heavy metal is chemically bound within the magnetite inverse
8 spinel structure.

9 A wide variety of heavy metals can be removed from water using the present
10 invention. Examples of the heavy metals which can be removed from water include lead,
11 manganese, cadmium, cobalt, mercury, nickel, and silver. In essence, the process is widely
12 applicable to transition metals, actinides, and lanthanides.

13 Once the magnetite (ferrite) is formed and the heavy metals are bound to the
14 magnetite, the resulting complex is flowed through a solid matrix. As mentioned above, the
15 matrix may, for example, be steel wool. Also as mentioned above, the steel wool may
16 display remnant magnetism, or it may be subject to an external magnetic field.

17 As the heavy metal-magnetite complex passes through the solid matrix, it is
18 magnetically bound to the matrix. Thus, the heavy metal is removed from the aqueous
19 system. Once the matrix becomes loaded with the bound magnetite it is a simple matter to
20 remove and dispose of the bound magnetite. One such removal process is to reverse flow
21 through the apparatus and increase the superficial velocity such that the magnetite is
22 physically removed from the solid magnetic matrix. Generally a reverse flow of water, or
23 more preferably an air-water mixture, is suitable. Flow rates somewhat higher than the initial
24 flow rates through the device are preferred. In particular, it is found that superficial
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1 velocities in the range of from about 3 cm/sec to about 10 cm/sec work well. This is in
2 contrast to forward superficial velocities in the range of about 1.0 cm/sec.

3 The heavy metal bound magnetite is then collected and disposed of. It is found that,
4 especially in the case of magnetite formed in situ, the heavy metal does not leach appreciably
5 after disposal. Therefore, it is possible to use inexpensive disposal methods.

6 The present invention also relates to an apparatus for achieving the heavy metal
7 remediation process described above. The apparatus can be constructed, for the most part
8 of conventional components. In basic terms, the apparatus of the present invention includes
9 a water conduit for introducing water containing heavy metals into the apparatus. The
10 apparatus also includes a conduit for introducing a quantity of magnetite, or the components
11 to synthesize magnetite in situ, into the apparatus. The water and the magnetite are mixed
12 in a reaction chamber such that at least a portion of the heavy metals are bound to the
13 magnetite. Next the mixture of water and heavy metal bound magnetite is introduced into
14 a magnetic separator configured such that magnetite is removed from the water by
15 application of a magnetic field. The separator preferably includes a solid matrix positioned
16 within the separator and containing a remnant magnetization. The treated water is then
17 conducted back out of the device by an outlet conduit.

18 As discussed above, the matrix within the separator may have remnant magnetism.
19 Alternatively, an external magnet is provided to produce the necessary magnetic field
20 gradients in the matrix material.

21 There are several advantages to the present invention over the conventional
22 technology of heavy metal removal. The present invention provides a much smaller facility
23 footprint, less chemical additives required and consequently less sludge produced than with
24 conventional processes. Magnetic separation will even work on elements that are not

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1 intrinsically ferromagnetic or paramagnetic by the proper seeding of iron based compounds
2 to the waste stream which act to scavenge the nonmagnetic contaminants.

3 The present invention demonstrates the several advantages of this technology. It has
4 been found that remnant field separator performance on commercial magnetite at particle
5 sizes greater than $5 \mu\text{m}$ is more than adequate. Collection in and purging of the matrix can
6 be controlled by superficial velocity and gas sparging. No magnetic field adjustment is
7 required. Remnant field matrices appear to be magnetically stable and require minimal
8 maintenance. Use of a graded matrix may effectively address a wider range of particle sizes
9 if that is required.

10 These and other objects, features, and advantages of the present invention will
11 become more fully apparent from the following description and appended claims, or may be
12 learned by the practice of the invention as set forth hereinafter.

13

14 **BRIEF DESCRIPTION OF THE DRAWINGS**

15 In order that the manner in which the above-recited and other advantages and objects
16 of the invention are obtained will be readily understood, a more particular description of the
17 invention briefly described above will be rendered by reference to specific embodiments
18 thereof which are illustrated in the appended drawings. Understanding that these drawings
19 depict only typical embodiments of the invention and are not therefore to be considered to
20 be limiting of its scope, the invention will be described and explained with additional
21 specificity and detail through the use of the accompanying drawings in which:

22 Figure 1 is a block diagram illustrating an embodiment of the present invention
23 utilizing a remnant magnetic field.

24 Figure 2 is a block diagram illustrating a further embodiment of the present
25 invention utilizing an external magnet.

1 DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

2 As discussed above, the present invention relates to effective, yet inexpensive,
3 methods and apparatus for removing heavy metals from water. This is a persistent and
4 difficult problem in environmental control and remediation. The present invention is based
5 upon the use of magnetite to bind heavy metals in water. Since magnetite is extremely
6 ferromagnetic, it is then a simple matter to remove the magnetite and bound heavy metals
7 from the water by application of a magnetic field.

8 In order to apply this invention to typical remediation work, it is desirable to
9 produce magnetites at relatively low temperature such that magnetite can be produced in situ.
10 The formation of magnetites down to temperature as low as 6⁰C and as high as 70⁰C has been
11 accomplished. Reaction times for seeded, in-situ formation, at 6⁰C are 15-45 minutes.
12 Studies have shown the ability to form magnetites, dependent on the nature of the waters in
13 which formation is achieved. For example, high quality magnetites have been produced
14 from distilled water and from mine water from the Leadville Mine Drainage Tunnel
15 Treatment Facility in Colorado (hereinafter "LMDT waters") at 70⁰C. As discussed above,
16 the procedure involves adding stoichiometric amounts of iron(II) and iron (III) sulfate to a
17 heated solution to be treated, adjusting the pH to 8-9 using sodium hydroxide. At this point
18 the colored suspension turns dark black and green, indicating the formation of magnetites
19 and green rust. After approximately a one hour reaction time, higher order magnetite/ferrite
20 crystals are observed.

21 It was initially observed that at low temperatures of 6⁰C, the LMDT water slowed
22 magnetite formation. Initially dissolved oxygen was believed to be an inhibitor due to
23 oxidation of the iron(II) present in solution; however, deoxygenation with argon did not fully
24 alleviate the problem. It was then concluded that the inhibition was apparently due to
25 competition from other ions for hydroxide or from formation of another solid phase that
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1 competes with magnetite formation. Since calcium and magnesium are the two principle
2 "other" ions in the LMDT water, formation efficacy in the presence of both of these at
3 concentrations reported at the LMDT facility was examined. It was observed that while
4 magnesium produced a slightly more flocculent product, it did not interfere with magnetite
5 formation whereas calcium inhibited the process. As will be discussed further in the
6 Examples section below, the process has been developed such that interference by calcium
7 in solution has been minimized.

8 It is believed that magnetite formation is a two stage process: (1) initial formation
9 of a "green rust" (Fe(II) oxy-hydroxides); (2) followed by dehydration and incorporation of
10 Fe(III) to form magnetite.

11 Remediation studies at 6°C have been carried out using lead(II) and manganese(II)
12 as test metals. The magnetite in-situ process effectively removes both lead and manganese
13 to the parts per billion (ppb) range. It is important to note that at very low Fe:M ratios,
14 incomplete magnetite/ferrite formation occurs as evidenced by some brown compound
15 precipitating from solution. However this is all removed when passed through a simple
16 magnetic separation device (a magnet with a steel wool column).

17 Remediation studies at 6°C, pH 9 have been carried out using cadmium(II),
18 cobalt(II) and lead(II) as test metals. Initially cadmium(II) removal was studied using both
19 distilled and LMDT water sources with a variety of magnetites and with various cadmium
20 contamination levels.

21 The magnetite in-situ process effectively removes cadmium from high and low
22 concentrations to the ppb or sub-ppb range, depending on the initial cadmium concentration
23 and iron doses. There is a dependence upon the nature of the magnetite used. The best
24 removal is observed for magnetites that are synthesized in the laboratory and used shortly
25 thereafter. Using this source, excellent removal is observed at a magnetite dose of 100ppm.
26

1 Although commercial magnetite is also effective in removing the target metal,
2 higher doses, up to 500ppm, are required. Surface activation of the commercial product is
3 also important in cadmium(II) remediation. This requires “soaking” the commercial
4 magnetite in 1.0M NaOH for 10-30 minutes followed by filtering off and washing the
5 magnetites with distilled water to remove any remaining base. Activation using 0.5M
6 Ba(OH)₂ shows equally effective activation.

7 In summary, in-situ formation of magnetites presents the presently preferred method
8 for heavy metal removal in both pure water and LMDT water. The use of preformed
9 magnetites is also an effective method for the remediation of heavy metals from LMDT
10 water sources. Further, it is found that combining seeding with preformed magnitite and in-
11 situ formation presents further improvement in some cases with respect to metal capture and
12 magnetite removal.

13 The present invention also involves an apparatus for accomplishing separation of
14 heavy metals from water. The presently preferred embodiments of the present invention will
15 be best understood by reference to the drawings, wherein like parts are designated by like
16 numerals throughout. It will be readily understood that the components of the present
17 invention, as generally described and illustrated in the figures herein, could be arranged and
18 designed in a variety of different configurations. Thus, the following more detailed
19 description of the embodiments of the apparatus, system, and method of the present
20 invention, as represented in Figures 1 and 2, is not intended to limit the scope of the
21 invention, as claimed, but is merely representative of presently preferred embodiments of the
22 invention.

23 Figure 1 is a diagram illustrating an apparatus 10 for implementing the process of
24 the present invention. A water source (not shown) is connected to the remainder of the
25 apparatus by a water inlet conduit which leads to a mixing chamber 14 for the formation of
26

1 a feed slurry. The water source may be a stream, lake, spring, or other source of
2 contaminated water.

3 Also provided is a source of magnetite, or the precursor components (Fe(II) and
4 Fe(III)) to form magnetite in situ. The magnetite or magnetite precursors are conducted to
5 the mixing chamber 14 as well. In the mixing chamber 14, the magnetite is formed, if
6 necessary. The heavy metals are allowed to contact the magnetite, or magnetite precursors,
7 and become bound to the magnetite.

8 Next the heavy metal-magnetite complex is conveyed by a conduit 16 and a pump 18
9 into a magnetic separator 20. There is a magnetic field applied within the magnetic separator
10 20 such that the magnetite and bound metals are removed from the water. In the
11 embodiment illustrated in Figure 1, a solid ferromagnetic matrix 22 is disposed within the
12 magnetic separator 20. The solid matrix 22 may, for example, comprise stainless steel wool.
13 As described elsewhere herein, the solid matrix 22 illustrated in Figure 1 has previously been
14 subjected to magnetism such that the solid matrix 22 now displays sufficient remnant
15 magnetism to bind the magnetite. In the expanded window portion of Figure 1, the manner
16 in which the magnetite particles 30 are bound to the steel wool matrix 22 is illustrated.

17 Once the metals and magnetite are removed from the water, the purified water leaves
18 the magnetic separator 20 via conduit 24 and forms a quantity of purified water 26 which can
19 be safely used or released into the environment. As illustrated in Figure 1, the purified water
20 may be held in a storage vessel 28.

21 Once the magnetite and bound metal is separated from the solid matrix it can be
22 collected in a collection vessel. As discussed herein, it is found that the magnetite-metal
23 complex is generally easily disposed of. Particularly in cases where the magnetite is formed
24 in situ, it is found that the metal does not leach out of the waste material. Accordingly, it is
25 possible to dispose of the waste in lower cost waste disposal facilities. Unlike many
26

1 conventional processes, the methods and apparatus of the present invention do not produce
2 large volumes of chemical waste.

3 Figure 2 illustrates an alternative embodiment of the device 50. Once again the
4 device has a mixing chamber 14. The mixing chamber 14 has an outlet conduit 16 and an
5 associated pump 18 for conveying the water/magnetite slurry or mixture to the separator 20.

6 The difference between the embodiment of the device illustrated in Figure 1 and that
7 illustrated in Figure 2 is that in Figure 2 an external source of magnetism is provided. This
8 may, for example, comprise an electromagnet 52. The other aspects of the invention are the
9 same and similar results are achieved.

10 Magnetic separation of this nature has been demonstrated to be effective. The
11 proposed method is based on utilizing the magnetic hysteresis found in certain hard magnetic
12 materials. Specifically, 430 series stainless steel wool possesses such characteristics and can
13 be used as a suitable matrix material for magnetic capture of the magnetite floc. By applying
14 a steady state magnetic field in excess of 2 tesla to this material, a saturation magnetization
15 can be achieved. Upon removal of the applied field, a remnant magnetic field remains in the
16 matrix material. As discussed above, it is also necessary to periodically remove the collected
17 magnetite from the matrix. Because of the relatively low magnetic field gradients in the
18 remnant field, it is possible to accomplish matrix cleaning using a high superficial velocity
19 backflush, if necessary accompanied by air sparging and/or mechanical vibration.

20 A tubular matrix containing the proper grade of 400 series stainless steel wool at the
21 optimum packing density is one of the presently preferred candidates. After determining the
22 optimum length, the cylindrical configuration is scalable by increasing its diameter to obtain
23 the desired volume. As discussed above, backflushing of the matrix can be accomplished
24 with an increased superficial velocity and air sparging.

25 Breakthrough tests, conducted under remnant field conditions, are used to define the
26 specific matrix capacity under various operating conditions. The specific matrix capacity

1 is a function of superficial velocity, magnetic field, magnetite particle size and carrier fluid
2 viscosity. The remnant field in the matrix has also been measured and determined that the
3 maximum value is approximately 800 G. In addition, the magnetite particle size in the slurry
4 will be similar to the seed material introduced to facilitate the in-situ formation of magnetite.
5 Therefore, the remaining variables affecting the breakthrough capacity are the superficial
6 velocity, the bed length and the effective matrix fiber diameter.

7 A number of matrix samples have been investigated because it is advantageous to
8 use the coarsest grade of steel wool that provides adequate magnetite removal. The coarser
9 grades are easier to backflush, which translates to shorter flush times and lower flush
10 volumes. The finer grades have higher capacity and increased capture efficiency.

11 Experimental results confirmed the utility of the methods of the present invention.
12 These results indicate that a separator design based on a single-pass cylindrical matrix of
13 uniform packing and containing a remnant magnetic field applied at two tesla is an
14 acceptable configuration. This design has the following attributes: (1) no active magnet is
15 required for normal operation of the separator, only for periodic recharge of the remnant
16 magnetic field; (2) backflushing can be accomplished by flowrate control and gas injection,
17 thus simplifying the configuration; (3) the matrix is modular, which enables convenient
18 scaleup, ease of replacement for maintenance and flexibility for continuous operation; and
19 (4) separator performance characteristics can be modified for seasonal variation of feed by
20 changing packing material; and (5) matrix packing material is commercially available and
21 inexpensive.

22 Thus, it can be seen that the use of magnetites to remove heavy metal contaminants
23 is effective regardless of the mode of application. The binding of heavy metals to
24 magnetites may be able to be enhanced with the selective use of organic chelators. The use
25 of remnant field magnets to perform magnetic separations has been established. These fields
26 appear stable over month-long time periods and the use of inexpensive stainless steel wool

1 matrices also provide good results. Separation of 5 micron sized particles is effective using
2 these remnant field magnetic separators. Both loading and unloading of the magnetic
3 separator can be controlled by flow velocity and gas sparging, respectively.

The present invention provides methods and apparatus for the remediation of heavy metals from a waste stream that requires inexpensive materials and equipment. Because the wastes generated from this approach are less, more compact than traditional metal hydroxides and robust with respect to conventional leaching in land fills, the disposal costs associated with this technique are reduced as well.

EXAMPLES

Example 1

As mentioned above, it appears that calcium is the principal interfering ion (83.5 ppm in LMDT waters) in the magnetite formation process.

Initially attempts were made to remove calcium from water by alkaline precipitation, followed by filtration and subsequent magnetite formation. The addition of sodium hydroxide to pH 11 followed by filtration of the white precipitate, assumed to be calcium hydroxide. Once treated, the water magnetites were successfully formed. Such an approach however, was deemed unacceptable however since almost any contaminating metal would also precipitate thereby rendering further treatment unnecessary. This high of a pH would also make the resulting sludge volumes enormous.

21 Next the addition of strong calcium complexing agents was tried (NTA, EDTA)
22 which worked, but again, the cost of these reagents were too high to form the basis of a
23 treatment plan. These experiments did confirm that calcium is the “bad” player in this
24 process.

25 The next attempt to circumvent this obstacle was to seed with small amounts of pre-
26 formed magnetite. Unlike the lack of success with the initial experiments using standard

1 magnetite synthesis, this approach produced good results toward low temperature synthesis
2 of magnetites.

3 The first experiments were conducted by adding 5 μm sized magnetite particles to
4 the water to be treated followed by stoichiometric additions of ferrous and ferric sulfates.
5 These solutions were deoxygenated using argon or nitrogen, chilled to 6°C and NaOH was
6 added to adjust the pH to approximately 8-9. The reaction was monitored visually by
7 watching the initially formed green floc change into black magnetite over 15-45 minutes.
8 The amounts of each substance and the results are shown in Table 1. The preformed
9 magnetites showed distinct differences in catalysis dependent upon their origin.
10 Commercially available magnetites showed less catalytic activity than preformed magnetites.
11

12 Table 1: Low Temperature (6°C) Seeding of Magnetites

magnetite added	Fe(II) sulfate	Fe (III) sulfate	water source	conversion to magnetite
100 ppm	31.2ppm	68.8ppm	SAMD	yes
0	31.2	68.8	SAMD	no
500	300	500	LMDT	yes
0	300	500	LMDT	no
216	83	133	distilled	yes
216	83	133	LMDT	yes
0	83	133	LMDT*	no

21 SAMD = simulate acid mind drain water

22 LMDT = actual Leadville facility water source

23 *15°

24 Regardless of which magnetite sources were used, it is readily apparent in Table 1
25 that magnetites are formed at 6°C using either distilled water or LMDT water samples when
26 seeded with magnetite. From work on the aforementioned experiments, it was shown that

1 the presence of calcium ions had a deleterious effect on the formation of magnetites. This
2 is believed to be due to a competition between formation of calcium hydroxide and magnetite
3 when the pH is adjusted to 9. Tests have been conducted to determine whether calcium is
4 removed by the preformed magnetite by surface adsorption. There is no indication that this
5 occurs. The calcium levels before and after suspension of magnetite are exactly the same.
6 Therefore, it can be concluded that the magnetite added actually catalyzes the growth of
7 magnetite crystals.

8

9 Example 2

10 Powder X-ray diffraction (hereinafter "XRD") experiments were performed on the
11 magnetites formed both from high and low temperature work on commercial magnetite and
12 magnetites (ferrites) synthesized from LMDT waters and synthesized magnetites with metal
13 substitutes. The results of these studies showed diffraction angles identical to commercially
14 available magnetites. This confirms that the process disclosed herein actually forms
15 magnetites and not some other dark colored iron oxide. Literature XRD spectra (JCPDS) of
16 maghemite and hematite were also compared. Very different lines are reported for these
17 forms of iron oxide which confirmed the synthesis of magnetite and not these other iron
18 oxides. Examples of XRD spectra are summarized in Table 2.

19

20 Table 2: XRD data on magnetites

21 Substrat	D-Spacing Values, in \$					
22 JCPDS	4.850	2.964	2.528	2.094	1.711	1.613
23 Commercial	4.795	2.947	2.516	2.086	1.707	1.608
24 Magnetite						

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1	synthetic	4.792	2.945	2.516	2.083	1.708	1.608
2	magnetite,						
3	70°C						
4	synthetic	peak not	2.953	2.523	2.085	1.703	1.607
5	magnetite,	resolved					
6	5°C						
7	synthetic, Hg,	peak not	2.934	2.512	2.082	1.701	1.604
8	70°C	resolved					
9	synthetic, Cu,	peak not	2.938	2.514	2.083	1.705	1.611
10	70°C	resolved					
11	synthetic,	peak not	2.953	2.523	2.085	1.703	1.607
12	Leadville,	resolved					
13	5°C						

14 Example 3

15 Removal of higher concentrations of metal contaminants have also been examined
 16 and these have yielded excellent results as well. These are shown in Tables 3 and 4.

18 **Table 3 ; Manganese Removal at varying Mn doses. T = 6.0°C.**

Iron dose:Metal Dose (mole ratios)	Initial Mn dose (ppm)	Mn remaining (ppm)
20:1	5	below detection limits
10:1	10	0.12
5:1	20	0.24
4:1	25	0.42
1.3:1	30	0.25

Table 4: Lead Removal at varying Pb doses. T = 6.0°C

Iron dose: Metal Dose (Mole ratios)	Initial Mn dose (ppm)	Mn remaining (ppm)
20:1	5	below detection limits
10:1	10	below detection limits
5:1	20	0.022
4.5:1	22	0.12

These studies showed that magnetite doses can remain fairly low, with respect to contaminant levels, and still provide good remediation.

The remediation of cadmium(II) from solution was also examined. In these studies magnetites were formed as described above and the magnetic separation was used to “filter” the water. In each instance, initial 50ppb cadmium levels were reduced to below a 1ppb detection limit. These experiments demonstrated the efficacy of the in-situ preparation method as well as magnetic separation.

Example 4

Test were performed to determine the ability of magnetite to remove cadmium from solution. Table 5 presents the results of those tests.

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Table 5: Removal of Cd from aqueous media

initial Cd level	magnetite dose	final Cd level	% removal
<u>unactivated commercial magnetite</u>			
distilled water source			
14ppm	100ppm	4.3 ppm	69
25ppm	100ppm	6ppm	76
38ppm	100ppm	2ppm	95
20ppm	500ppm	2ppm	90
30ppm	500ppm	6ppm	80
<u>unactivated commercial magnetite</u>			
Pvville water source			
390ppb	100ppm	218ppb	44
390ppb	250ppm	82ppb	79
390ppb	500ppm	22ppb	94
<u>activated commercial magnetite</u>			
Leadville water source			
390ppb	500ppm	4ppb	99
390ppb	500ppm	<4 ppb	>80
<u>synthesized magnetites</u>			
Leadville water source			
20ppb	100ppm	below 1 ppb detection limit	>99

Example 5

Tests were performed to determine the ability of magnetite to remove cadmium from solution. Table 6 presents the results of those tests.

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2 **Table 6: Removal of Cd from aqueous media**

initial Cd level	magnetite dose	final Cd level	% removal
unactivated commercial magnetite			
Pbville water source			
200ppb	100ppm	41ppb	80
200ppb	250ppm	2ppb	99
200ppb	500ppm	<2ppb	>99

8 Tests were performed to determine the ability of magnetite to remove lead from
9 solution. Table 7 presents the results of those tests
10

11 **Table 7: Removal of Pb from aqueous media**

initial Pb level	magnetite dose	final Pb level	% removal
<u>unactivated commercial magnetite</u>			
Pbville water source			
5 ppm	25ppm	53.4ppb	99
5 ppm	50ppm	63.3ppb	99
5 ppm	75ppm	2.6ppb	>99
5 ppm	100ppm	below det limit	>99
10ppm	100ppm	90.9ppb	99
15 ppm	100ppm	130ppb	99
20 ppm	100ppm	133.3ppb	99

1 **Example 6**

2 *Binding in the presence of organics*

3 Since earlier studies had shown that added organics can influence the removal of
4 heavy metals using magnetites, similar studies were carried out in the presence and absence
5 of selected co-contaminants. Lead(II) was selected as the target metal since it has shown the
6 best experimental reproducibility. The experiments were carried out as described above
7 except that various concentrations of organic chelators were also added to the solution. The
8 initial lead concentration is 10^{-5} M.

9 Three structurally related chelating agents were studied to determine whether they
10 can compete effectively with the magnetite surface for the Pb²⁺ ion. The chelators were
11 acetate, oxalate and malonate as derived from the parent acids. These three were used
12 because of their structural similarities to each other as well as to functional groups found in
13 humic acids and common man-made chelators such as EDTA.

14 There were significant differences between acetate or malonate being present versus
15 no organics at all. At the highest pH used, greater than 90% removal of lead was observed
16 for no organics present. This is in contrast to when acetic acid or malonic acid was present.
17 A marked decrease in removal efficiencies was observed, even at the 10^{-5} M level, which is
18 approximately where the initial lead concentration was set. Even at the highest pHs studied,
19 no greater than about 65% removal of lead was observed. This is believed to represent
20 competition between the chelator with the magnetite for the lead ion. At the 10^{-4} M
21 concentration, the lead is probably coordinated by two or three organic ligands to give the
22 lead complex an overall negative charge since each ligand has a negative charge when fully
23 deprotonated. The binding constants for lead (II) with these ligands range between 10^2 to 10^6 .
24 As the pH of the solution is raised, the charge on the magnetite surface becomes more
25 negative and unable to bind the acetato or malononatoplumbate(II) ion.

26

1 In this study, addition of oxalic acid to the solution enhances the removal of lead
2 from solution. Although this could be due to precipitation of lead oxalate, the concentrations
3 used in this study do not exceed the solubility of lead oxalate ($K_{sp} = 10^{-8}$) and at the highest
4 oxalate concentration in this study $Q_{sp} = 10^{-9}$. Control experiments where the lead and
5 oxalate ions are added in the absence of magnetite show no decrease in the lead
6 concentrations before and after mixing, except at pH 10, where a decrease that may
7 tentatively be attributed to precipitation of PbC_2O_4 is observed. At the lower pHs however,
8 no precipitation of lead(II) oxalate or lead(II) hydroxide was detected.

9 The present invention may be embodied in other specific forms without departing
10 from its spirit or essential characteristics. The described embodiments are to be considered
11 in all respects only as illustrative and not restrictive. The scope of the invention is, therefore,
12 indicated by the appended claims rather than by the foregoing description. All changes
13 which come within the meaning and range of equivalency of the claims are to be embraced
14 within their scope.

15 What is claimed and desired to be secured by United States Letters Patent is:

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